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Behavioral Modeling of Polar Power Amplifiers Based on X-parameters by Characterizing Envelope Path using Tunable Low-pass Filters

Yelin Wang
Department of Electronic Systems, Aalborg University, Denmark

***Abstract*— X-parameters are developed as a superset of S-parameters and they are suitable for modeling systems having only radio-frequency (RF) and DC ports. For a polar power amplifier (PA), the envelope of the input modulated signal is applied at the envelope port, which is neither an RF nor a DC port. In this case, X-parameter may fail to characterize the behavior of the envelope path and consequently the polar PA. To solve the problem, this paper proposes a method where the nonlinearity on the RF-phase path of a polar PA is characterized by X-parameters and the frequency behavior on the envelope path is modeled by a tunable low-pass filter. The two models are then combined to establish the behavioral model for the polar PA. The concept is preliminarily validated on a 2.25GHz polar PA for WCDMA/EDGE applications in a 0.18µm CMOS process.**

***Keywords*— X-parameters, behavioral modeling, polar power amplifiers, envelope tracking, CMOS technology**

I. INTRODUCTION

X-parameters, developed as an extension to S-parameters, are capable of modeling nonlinear systems [1]. Their capability of modeling polar and ET PAs is explored recently in [2], [3]. The problem of applying X-parameters to polar and ET PAs lies in the fact that they are basically suitable for systems having only RF and DC ports. In polar and ET PAs, the envelope signal is modulated separately by an amplitude modulator and then coupled with the RF phase to produce the output RF signal. The bandwidth of the envelope signal is several times larger than that of the baseband [4], and the amplitude modulator usually has a low-pass characteristic [5]. The envelope port is neither an RF nor a DC port. X-parameters may fail to characterize the coupling between the envelope port and RF output port (namely, the dynamics, or the low-pass characteristic, on the envelope path). In [3], to solve the problem described above, the authors proposed a method where the polar or ET PA is treated as a mixer, with the envelope port treated as, i.e., the LO port. Utilizing the principle of X-parameters for mixers [6], three-port X-parameters can be measured for a polar or ET PA. However, the limitation of this method lies in the available minimum frequency of hardware, namely, Agilent PNA-X, which measures X-parameters. The minimum operating frequency of PNA-X is 10 MHz, meaning the dynamics on the envelope path can only be characterized at frequencies higher than 10MHz (i.e., 10/20/30/40/... MHz), and the information below 10MHz cannot be captured. This may cause inaccuracy to the model, especially in the case where the bandwidth of the frequency characteristic of the envelope path is less than 10MHz.

In [7], we proposed an alternative solution to the problem for a polar PA. In this solution, the nonlinearity on the RF phase path and the dynamics on the envelope path are modelled separately: the former is characterized by standard two-port X-parameters, and the latter is modeled by a simple low-pass filter (LPF). These two models are then combined to establish a complete behavioral model for the polar PA. The advantage of this solution over [3] is that the dynamics on the envelope path can always be accurately characterized. However, the solution is only suitable for a group of polar PAs where the envelope path has an amplitude-independent low-pass frequency characteristic (so that it can be modelled by a simple LPF). As a continuity and extension to our previous work in [7], this paper studies more complicated case where the envelope path has an amplitude-dependent frequency characteristic. An advanced method is proposed where the dynamics on the envelope path is modeled by using a tunable LPF. The concept is preliminarily validated by simulations on a WCDMA/EDGE polar PA designed in a 0.18*µm* CMOS process.

II. X-PARAMETER FUNDAMENTALS

X-parameters are parameters of a poly-harmonic distortion model and the basic equation of the model is written as [1]:

$$b_{ik} = X_{ik}^{F}(|a_{11}|)P^{k} + \sum_{(i,j)\neq(1,1)} \{X_{ik,jl}^{S}(|a_{11}|)P^{k-l}a_{jl} + X_{ik,jl}^{T}(|a_{11}|)P^{k+l}a_{jl}^{*}\} \quad (1)$$

where b and a represent the outgoing and incident waves of the device under test (DUT), (i, j) and (k, l) are port and harmonic indices, $P = e^{j\cdot\varphi(a_{11})}$ represents the phase of the large-signal input a_{11}, and a_{jl} is the parameter extraction tone and has small magnitude compared to a_{11} . a_{jl}^* is the complex conjugate of a_{jl} . $X_{ik}^F, X_{ik,jl}^S, X_{ik,jl}^T \in \mathbb{C}$ are X-parameters, dependent on the magnitude of a_{11} . F-type X-parameter X_{ik}^F describes the DUT's response to the large-signal a_{11} ; S/T-type X-parameters $X_{ik,jl}^S$ and $X_{ik,jl}^T$ describes how the parameter extraction tone a_{jl} contributes to the outgoing *b*-waves. During X-parameter measurement, the DUT is driven by the large-signal a_{11} and meanwhile the parameter extraction tone a_{jl} is injected to the ports of the DUT by internal source of the PNA-X. a_{jl} with different phases are applied and the X-parameters are extracted by solving a set of equation described in (1) [1].

In (1), X-parameters are dependent only on the magnitude of a_{11} . In reality, other dependence, such as DC biasing and load impedance, need also to be included. In those cases, (1) needs to be extended to:

$$b_{ik} = X_{ik}^F(|a_{11}|, V_B, Z_L)P^k + \sum_{(i,j)\neq(1,1)} X_{ik,jl}^S(|a_{11}|, V_B, Z_L)P^{k-l}a_{jl} + \sum_{(i,j)\neq(1,1)} X_{ik,jl}^T(|a_{11}|, V_B, Z_L)P^{k+l}a_{jl}^* \quad (2)$$

where V_B and Z_L represent the DC biasing condition and load impedance of the DUT, respectively. (2) is the basic equation used in this study.

III. MODEL CREATION

A. *Proposed Solution*

As described, the problem of applying X-parameters to polar and ET PAs modeling is that they cannot capture the dynamics on the envelope path. For a polar or ET PA, the phase and envelope of the input modulated signal are applied at different port, shown in Fig. 1. The envelope is a baseband signal and usually has a bandwidth of tens of MHz. The envelope port is neither an RF nor a DC port, whereas X-parameters are suitable to systems having only RF and DC ports.

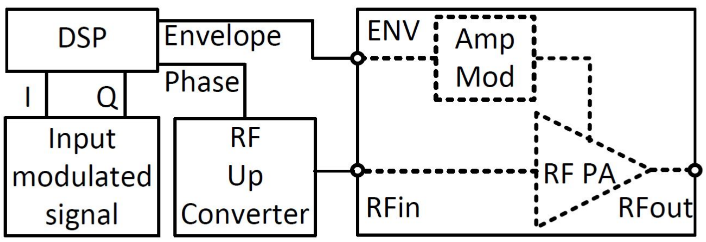

Fig. 1: Simplified polar and ET PA with a nonlinear RF PA.

The dynamic behavior on the envelope path is determined by the frequency characteristic of the amplitude modulator and bandwidth of the output matching network. The amplitude modulator can be an envelope shaper, a low-dropout regulator and so on, and it usually has a low-pass frequency characteristic [5]. It means that the envelope path behaves usually as a LPF. To model the envelope path, a straightforward way is to use a LPF to simulate the dynamic behavior on the path. Fig. 2 illustrates the proposed model to solve the problem of applying X-parameters to polar and ET PA modeling. A two-port X-parameters model with a DC input port represents the nonlinearity on the RF phase path when the envelope port is excited by DC voltages. A simple LPF or tunable LPF simulating the dynamic behavior on the envelope path is connected to the DC port of the X-parameters model, establishing a complete behavioral model for the polar or ET PA. The choice between a simple LPF and tunable LPF depends on whether the frequency response of the envelope path is amplitude-independent or not.

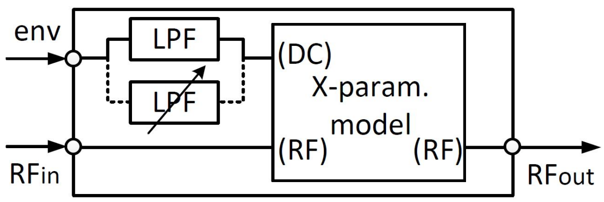

Fig. 2: Proposed model to solve the problem of applying X-parameters to modeling of polar and ET PAs.

B. Device Under Test

The DUT is a 2.25GHz two-stage cascode polar PA in a 0.18*µm* CMOS process and the schematic is shown in Fig. 3 [8]. In polar operation, the envelope signal is applied at Vcasc port and modulated by the cascode transistor M3, and the phase information is carried by a constant envelope RF signal which is applied at the RF IN port of the PA [8]. Transistor M2 is designed to be operating in switch-mode to maximize the efficiency of the PA. To ensure that M2 acts always as a switch, two requirements should be met: (1) the instantaneous voltage applied at Vcasc port should be larger than 0.6V (but lower than 1.8V to avoid damage), and (2) the input power of the PA should be large enough to drive M2 into saturation and it is about 3dBm in this work.

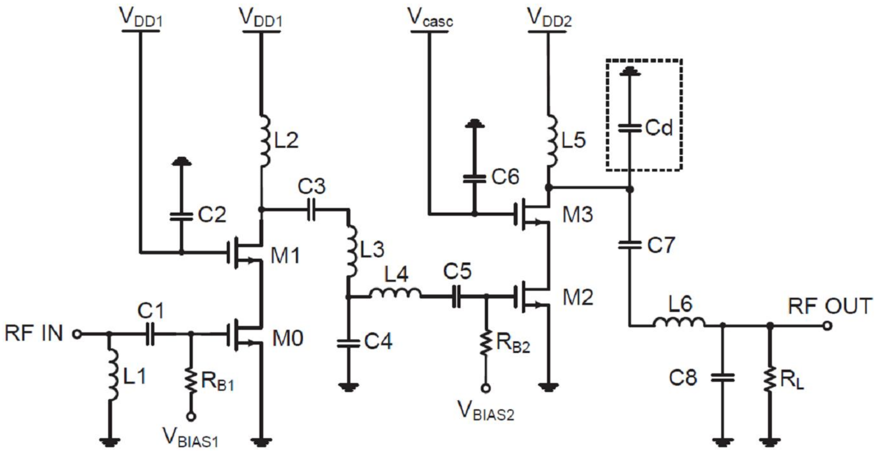

Fig. 3: Schematic of the two-stage polar PA under test [8].

C. Modeling Nonlinearity on RF Phase Path

X-parameter simulation is performed in Agilent Advanced Design System (ADS) to extract the X-parameters characterizing the nonlinearity on the RF phase path of the DUT. In the simulation, the input is a single-tone at 2.25 GHz with 3dBm average power, ensuring M2 operating as a switch; DC voltages are applied at Vcasc port and swept from 0.6 to 1.8V in steps of 0.05V. The load is fixed at 50 (which the PA is matched to) in this work. At each sweeping point of Vcasc, magnitude and phase of all incident and outgoing waves of the PA are simulated. Based on that, the corresponding X-parameters are calculated and they are parameterized against Vcasc as described in (2). An X-parameter model is created by fitting the extracted X-parameters to the framework of poly-harmonic distortion model (the 'XnP' component) in ADS.

As discussed, the created X-parameter model is expected to be able to characterize the nonlinearity on the RF phase path of the polar PA under test when its envelope port (the Vcasc port) is excited by DC voltages. Fig. 4 plots the comparison of the simulated static AM/AM and AM/PM curves between the transistor model and created X-parameter model of the DUT. Good matching can be observed from the figure, meaning the nonlinearity on the RF phase path can be precisely modeled by the created X-parameter model.

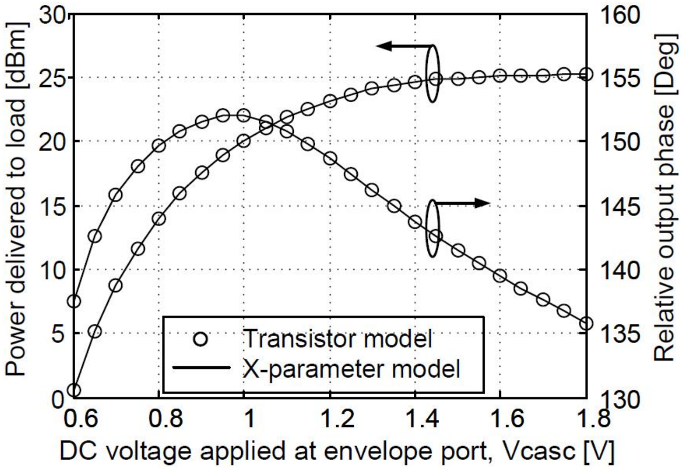

Fig. 4: Simulated power delivered to load (AM/AM) and relative output phase (AM/PM) versus Vcasc of the DUT.

D. Modeling Dynamics on Envelope Path

To To model the dynamics on the envelope path, the objective is to figure out the frequency characteristic on the path and model it using a tunable LPF. A single-tone at 2.25 GHz with 3dBm power is applied to the RF IN port of the PA to operate M2 as a switch. Meanwhile, a testing time-varying envelope signal *vein*(*t*) is applied to the Vcasc port:

$$v_{ein}(t) = V_{dcin} + A_{in}\cos(\omega_m t) \tag{3}$$

The testing envelope signal is basically a sinusoidal signal at a (angular) frequency of ω_m with an amplitude of A_{in} and a DC offset of V_{dcin} [7]. The output RF signal $v_{out}(t)$ of the polar PA under test can be expressed by:

$$v_{out}(t) = v_{eout}(t)\cos(\omega_{rf} t + \phi_{rf}(t)) \tag{4}$$

where $\phi_{rf}(t)$ represents the phase error between the input and output RF signals and is characterized by the previously created X-parameter model. *veout*(*t*) is the output time varying envelope signal and is expressed as:

$$v_{eout}(t) = V_{dcout} + A_{out}\cos(\omega_m t + \phi_{out}) \tag{5}$$

By Comparing (3) and (5), it is possible to find the relation of amplitude and phase between the input and output time-varying envelope signal at frequency ω_m. Sweeping ω_m, these relation (dependent on ω_m) can be written as:

$$\beta(\omega_m) = \frac{A_{out}(\omega_m)}{A_{in}} \tag{6a}$$

$$\phi(\omega_m) = \phi_{out}(\omega_m) \tag{6b}$$

where $\beta(\omega_m)$ and $\phi(\omega_m)$ are the frequency characteristics of the envelope path which need to be figured out and modeled.

Fig. 5 plots some representative examples of the simulated frequency response on the envelope path of the DUT. Simulation with different testing envelope signal $v_{ein}(t)$ shown in (3) are performed: DC offset V_{dcin} varies in the range of 0.6 to 1.8V, while the small-signal amplitude A_{in} is kept unchanged at 0.05V. It can be seen that the frequency characteristic on the envelope path is low-pass-like and dependent on V_{dcin}. A tunable LPF (or, in fact, a bank of LPFs) is made in MATLAB to model the simulated frequency characteristic of the path. The simplified structure of the tunable LPF is shown in Fig. 6. The varying range of V_{dcin} [0.6, 1.8] is split evenly into smaller ranges, i.e., [0.6, 0.62], (0.62, 0.64] ...... (1.78, 1.8]. The detector detects the instantaneous amplitude of the input signal (namely, the real envelope signal), and determines which small range the amplitude falls in, and decides which LPF should be activated at this time instant. As an example, if the instantaneous amplitude of the input signal is 0.63V falling in the range of (0.62, 0.64], the LPF modeling the simulated frequency characteristic of the envelope path with V_{dcin} equal to 0.64V will be activated at this time instant. There exists error due to the approximation in this method. But the error can be diminished by narrowing the small ranges even further. In the bank of LPFs in Fig. 6, one single LPF is designed according to the bandwidth of the corresponding simulated frequency response of the envelope path.

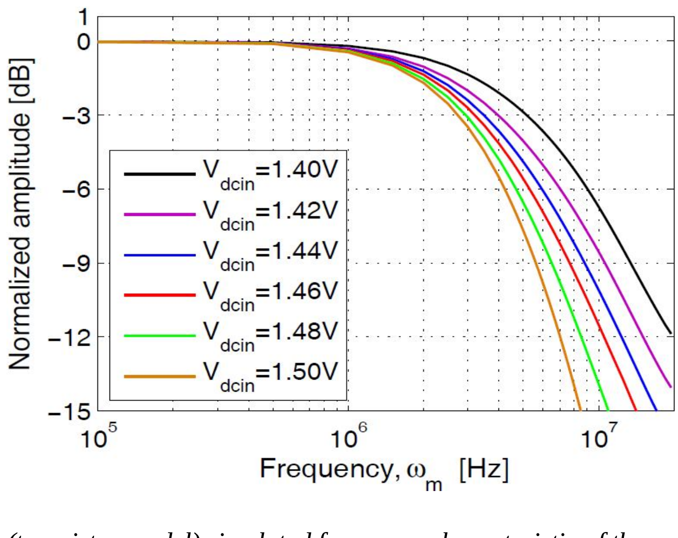

Fig. 5: Examples of the (transistor model) simulated frequency characteristic of the envelope path of the DUT.

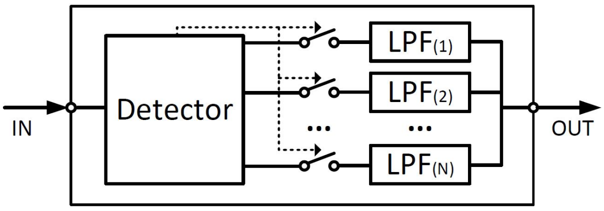

Fig. 6: Simplified structure of the designed tunable LPF.

IV. VALIDATION RESULTS

The nonlinearity on the RF phase path and dynamics on the envelope path of the DUT are now modeled by an X-parameter model and a tunable LPF, respectively. These two models are then combined according to Fig. 2 to establish the complete behavioral model for the DUT. Modulated signal simulations are performed on the transistor model as well as on the created behavioral model of the DUT. Simulated output RF signals from the two models are compared in order to validate the model as well as the proposed method.

To validate the created behavioral model of the DUT, it is critical to check if it adequate to model the envelope path of the DUT by a tunable LPF. In light of that, modulated signals with different channel bandwidths are used as the testing signals in the simulations. In this work, the testing modulated signals are standard WCDMA signals but with scaled bandwidths which is swept from 0.1 to 60MHz. The instantaneous voltage of the envelope is adjusted to be from 0.6 to 1.8V. Fig. 7 - Fig. 9 show the simulation results. Fig. 7 plots the simulated spectra of the output signals from transistor model and created behavioral model of the DUT under a testing input signal with 40MHz bandwidth. The spectrum of the input signal is also plotted as a reference. Fig. 8 and Fig. 9 plot the error vector magnitude (EVM) and adjacent-channel-power-ratio (ACPR) as a function of the bandwidth of the testing input modulated signal from the two models of the DUT. Good matching can be observed from the results: the maximum difference between the simulated EVM and ACPR from the transistor model and created behavioral model of the DUT are about 2.5%-point and 3dB, respectively. The created behavioral model and the proposed method to solve the problem of applying X-parameters to polar and ET PAs can be preliminarily validated from those simulation results.

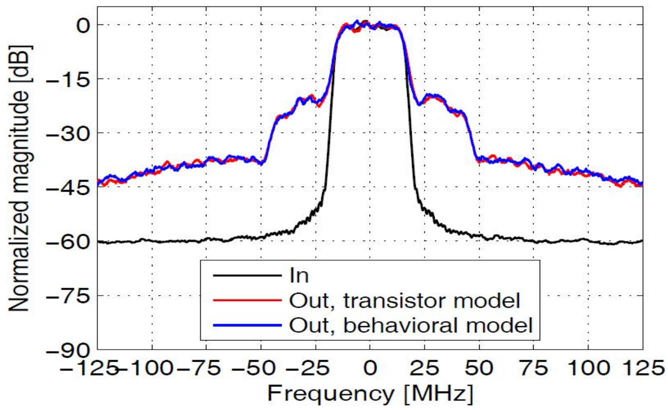

Fig. 7: An example of the simulated spectra of the output signals from the transistor model and created behavioral model of the DUT. The input modulated signal has 40MHz bandwidth.

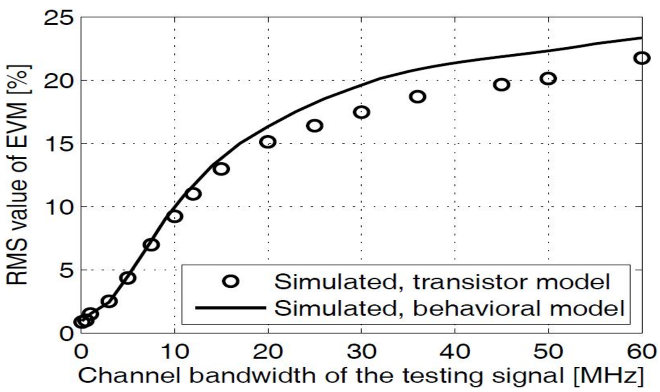

Fig. 8: A comparison of the simulated RMS EVM from the transistor model and created behavioral model of the DUT.

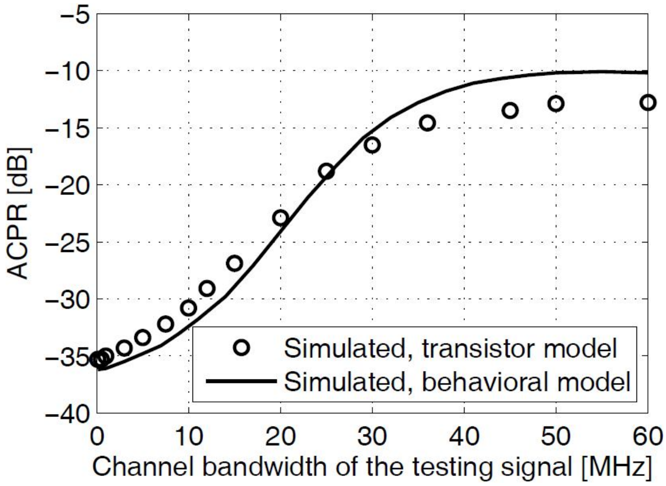

Fig. 9: A comparison of the simulated ACPR from the transistor model and created behavioral model of the DUT.

V. CONCLUSIONS

X-parameters are suitable for modeling systems that have only RF and DC ports (two-port systems). The paper analyzes the problem of applying X-parameters to polar and ET Pas (three-port systems), where the envelope port is excited by a varying envelope signal which is neither an RF nor a DC signal. To solve the problem, this work proposes a straightforward method, where the RF phase path and envelope path of a polar or ET PA are modeled by a static two-port X-parameter model and a tunable LPF, respectively. The proposed method is applied to a two-stage polar PA designed in a 0.18*μm* CMOS process. The validity of the proposed method is preliminarily proved by simulations. The work presented in this paper are based only on simulations and the effect of load mismatch of the PA is not studied as well. To study the subject more deeply, the focus of future work will be put on practical measurement where load-dependent X-parameters will be employed.

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REFERENCES

[1] J. Verspecht and D. E. Root: “Poly-harmonic distortion modeling,” *IEEE Microwave Mag*azine, vol. 7, no. 3, pp. 44-57, 2006.

[2] H. Jang, A. Zai, T. Reveyrand, P. Roblin, Z. Popovic and D. E. Root: “ Simulation and measurement-based X-parameter models for power amplifiers with envelope tracking,” in *IEEE MTT-S International Microwave Symposium Digest (MTT)*, Seattle, WA, Jun. 2013, 4p.

[3] G. Casini, A. Cidronali and G. Manes: “Investigation of X-parameters modeling for accurate envelope tracking power amplifier system simulations,” in *IEEE MTT-S International Microwave Symposium Digest (MTT)*, Seattle, WA, Jun. 2013, 4p.

[4] J. Groe: “Polar transmitters for wireless communications,” *IEEE Communication Mag*azine, vol. 45, no. 9, pp. 58-63, 2007.

[5] P. Reynaert and M. Steyaert, *RF Power Amplifiers for Mobile Communications*. Dordrecht: Springer, 2006.

[6] C. Xie, T. Zhang and D. Liu: “Using X-parameters to model mixers,” in *IEEE International Conference on Microwave and Millimeter Wave Technology (ICMMT)*, Shenzhen, China, May 2012, 3p.

[7] Y. Wang, T. S. Nielsen, D. Sira, O. K. Jensen and T. Larsen: “X-parameter- based modelling of polar modulated power amplifiers,” *IET Microwaves, Antennas & Propagation*., vol. 7, no. 14, pp. 1161-1167, 2013.

[8] D. Sira, *CMOS Power Amplifiers for Wireless Communication Systems*. Ph.D. Dissertation, Aalborg University, Denmark, Dec. 2010.

